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14. ABSTRACT
A radiation test plan for thin-film photovoltaic technologies focused on a MEO flight experiment is outlined. The proton and electron radiation response of thin film, amorphous Si solar cells and $CuInGaSe_2$ solar cells, with and without space coatings, is presented. The degradation of the photovoltaic output under penetrating and junction-damaging proton irradiation, and 0.6 MeV and 1 MeV electron irradiation,is measured and examined. The experimental data are presented and analyzed. These data will form the basis for an on-orbit prediction model as applied to a high-radiation MEO orbit.

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THIN-FILM PHOTOVOLTAIC PROTON AND ELECTRON RADIATION TESTING FOR A MEO ORBIT

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ABSTRACT

A radiation test plan for thin-film photovoltaic technologies focused on a MEO flight experiment is outlined. The proton and electron radiation response of thin film, amorphous Si solar cells and $CuInGaSe_2$ solar cells, with and without space coatings, is presented. The degradation of the photovoltaic output under penetrating and junction-damaging proton irradiation, and 0.6 MeV and 1 MeV electron irradiation, is measured and examined. The experimental data are presented and analyzed. These data will form the basis for an on-orbit prediction model as applied to a high-radiation MEO orbit.

INTRODUCTION

On-orbit satellite power requirements have been steadily increasing over the years for both commercial and military applications. The primary constraining factors for on-orbit power are solar array mass and launch vehicle fairing stowage volume. The solar array area, and hence maximum power available, is then constrained by these factors. Current space power generation technology is limited to approximately 30-50 kW due to inefficient stowage and low mass efficiency. Crystalline solar cells also degrade under exposure to the space radiation environment, even with protective coverglass. The peak performance of today's state-of-the-practice high efficiency crystalline solar cells will degrade by 10-15% after 15 years in a typical geostationary orbit, and up to 50% in orbits with high proton fluxes. This is one reason the Medium Earth Orbits (MEO), which are attractive from a global coverage versus number of satellites trade, are used by so few programs. In such an orbit, the solar array must provide twice the power at beginning of life as required at end of life, creating power and mass constraints.

Emerging thin-film photovoltaics (TFPV) for space power offer major improvements in power per stowed volume and power per mass over state-of-the-practice space power technology, and have demonstrated high radiation resistance to both electrons and protons in ground-test simulations along with significant self annealing properties. Such properties will enable future space power requirements to be met, particularly in the harsh MEO environment. For TFPV to be transitioned to operational space use, their on-orbit performance must be understood and well modeled. This entails a solid understanding of TFPV behavior in the space radiation environment. Many groups, including The Air Force Research Laboratory (AFRL) Space Vehicles Directorate and The Aerospace Corporation, have undertaken radiation testing and thermal annealing of amorphous silicon (a-Si) and $CuInGaSe_2$ (CIGS) technologies [1-6 and the references therein]. AFRL is now undertaking the most complete qualification-type testing of two thin-film PV technologies from three different vendors, with and without a thin-film space coating. In particular, AFRL, collaborating with Naval Research Laboratory (NRL), Jet Propulsion Laboratory (JPL), and The Aerospace Corporation, is performing an in-depth proton and electron radiation study, targeting performance in a MEO orbit to support a future space flight experiment. This work focuses primarily on providing the radiation damage and recovery data required to support an accurate on-orbit performance model for each technology. In addition, the radiation resistance afforded by thin space coatings, developed as "coverglass replacements" to enable TFPV technologies to withstand the harsh space environment and still meet optical, mechanical, thermal, and electrostatic discharge requirements, will be assessed through comparisons of coated and uncoated cells.

In this paper, the authors summarize the results to date for a-Si and CIGS exposure to > 500 keV protons and 0.6 MeV and 1 MeV electrons.

EXPERIMENTAL PLAN

Solar cells have been acquired from three vendors: one providing a-Si technology and two providing CIGS technology, all on flexible substrates. Each vendor provided solar cells without a space coating and JDS Uniphase applied a specially-formulated space coating to a quantity of cells from each vendor. In addition, the a-Si vendor provided solar cells with their proprietary coating. Both coated and uncoated solar cells were included in all radiation testing.

One MEO orbit of interest contains high fluxes (>10^{13}/cm^2/year) of protons with energies less than 1 MeV, and moderate fluxes (>10^{11}/cm^2/year) of electrons with energies less than 1 MeV (based on SPENVIS calculations, [7]). See Figure 1. A model of this orbit was used to determine the appropriate electron and proton test energies and fluences. Recognizing that the low-energy radiation spectrum of this orbit is still unknown to a large extent, fluences were extended to ensure full coverage. To further enhance the understanding of proton damage in particular, the Monte-Carlo TRIM model [8] was used to predict the amount of proton damage to each junction and to the space coating. The expected proton energy range is 20 keV to 3 MeV, with irradiations >500 keV performed at the Naval Research Laboratory (NRL) and irradiations <400 keV performed at The Aerospace Corporation. The expected electron energy range is 0.5 MeV to 6 MeV, with irradiation performed at the NASA Jet Propulsion Laboratory (JPL).

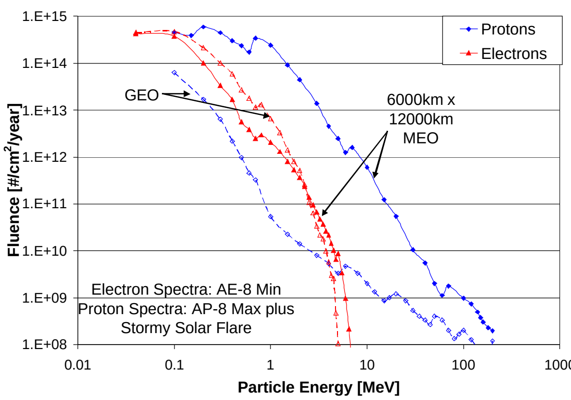

Figure 1. Electron and proton fluence spectra for a GEO orbit and a high-radiation MEO orbit using the traditional AP8 and AE8 radiation models.

CIGS and a-Si have both shown recovery under annealing at relatively low temperatures and under illumination [1-6]. The target of this work is to calculate both the damage rate due to irradiation and the recovery rate due to annealing. A sampling of proton irradiation under illumination is performed to simulate the annealing influence of sunlight. Non-illuminated irradiations (electron and proton) are performed at room temperature with the solar cells at open circuit. Illuminated irradiations are performed at ~65ºC under forward voltage bias conditions. Details are described elsewhere [1, 3]. Table 1 outlines the irradiation test plan. The solar cell manufacturers are identified by number only. The chosen energies span the expected range on orbit, and bound the expected minimum and maximum damage points in each solar cell type. All initial irradiations are completed, except those shown in italics. The remaining irradiations are underway, as are selective annealing experiments. See References 2 and 9 for details and recent results of irradiations performed at The Aerospace Corporation.

Table 1- Irradiation Test Plan Summary

Cell Type	Configuration	Energy	Fluence Range [#/cm^2]
Proton Testing at NRL			
a-Si V1	Bare JDSU Coating Prop. Coating	2 MeV	4E12 to 1E15, 1E14 Illum. *JDSU Illum.*
a-Si V1	JDSU Coating	600 keV	6E11 to 5E13, *Illum.*
CIGS V2	JDSU Coating	3 MeV	4E11 to 8E14
CIGS V2	JDSU Coating	940 keV	2E11 to 6E13
CIGS V3	Bare	3 MeV	4E11 to 8E14, *Illum.*
Electron Testing at JPL			
a-Si V1 CIGS V2 *CIGS V3*	Bare	1 MeV	1E13 to 1E15
a-Si V1 a-Si V1 CIGS V2 *CIGS V3*	JDSU Coating Prop. Coating JDSU Coating *Bare*	0.6 MeV 1 MeV *6 MeV*	5E13 to 1E15 1E13 to 1E15 *1E9 to 2E10*

For each irradiation, AFRL mounted four or five small-area cells (<20 cm^2) on a stainless steel plate and fitted them with wire contacts to reduce handling damage. A single-junction GaAs solar cell was also irradiated as a control sample in most cases. The cells were performance-tested under simulated AM0 illumination at AFRL and sent to NRL or JPL for irradiation. In each case, the solar cells were exposed to increasing fluences at a given particle energy in succession, with simulated AM0 performance testing occurring at the respective lab (NRL or JPL) after each exposure. The data were sent to AFRL for analysis.

TEST RESULTS

Proton Irradiation

Figure 2 compares normalized maximum power (Pmp) as a function of increasing proton fluence for all irradiations performed at NRL on a-Si V1. Data points are averages of four or five solar cell results, and the error bars represent the standard deviation. The solid lines represent results for 2 MeV proton irradiations (i.e. fully penetrating) in the dark. The dashed line represents the results for 600 keV proton irradiation, modeled as highly damaging. The open symbols represent the results for 2 MeV proton irradiations under illumination, as described in Ref. 3. Note that the fluences used are at least two orders of magnitude higher than what is generally used for assessing Low-Earth-Orbit (LEO) and GEO orbits.

Focusing on the solid lines demonstrates the effect of fully penetrating proton irradiation on the space coatings, in this case both the JDSU coating and the a-Si V1 proprietary coating. Significant degradation is observed for bare and coated cells. The degradation is primarily in the Fill Factor (FF) (not shown), dominated by current density loss. Data for the JDSU coating under 2 MeV irradiation show slightly more degradation as compared with the bare samples, and the proprietary coating slightly less degradation, but the differences are within the error bars. This demonstrates that the space coating does not detract from the radiation hardness of the solar cell structure.

The next step in assessing the effect of the coating is to implant low energy protons into the coating layer of coated solar cells. This work is ongoing at The Aerospace Corporation and the results will be discussed at a later

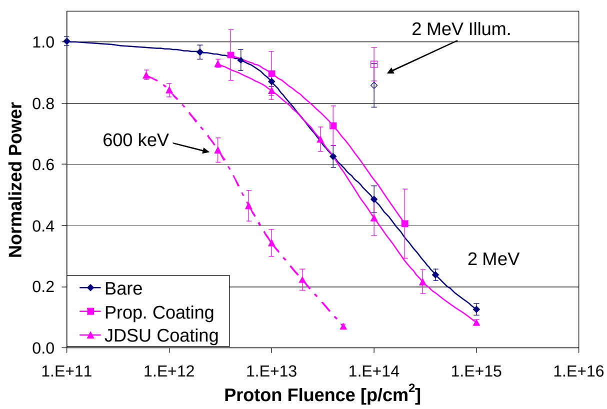

Figure 2. Normalized power as a function of proton fluence for a-Si V1. Solid lines: 2 MeV protons, dark. Dashed line: 600 keV protons, dark. Open symbols: 2 MeV proton illuminated.

date.

The open symbols compared with the solid lines demonstrate the effects of penetrating irradiation under illumination. It is obvious that irradiation under simulated flight-like conditions (illumination, elevated temperature [~50-65ºC], voltage bias) has a positive annealing influence on these a-Si solar cells. At the same fluence in the dark, the FF degraded by ~40%, but under the flight-like conditions, FF degraded less than 10% for both bare and coated a-Si samples. Additionally, Isc and Voc showed less than 5% degradation, compared with 12-17% under dark conditions. It is worth mentioning that these cells were not light-stabilized prior to irradiation; hence, the degradation observed is likely due to a combination of Staebler-Wronski degradation and proton damage. See Ref. 10 for results of light-induced degradation of a-Si V1 solar cells.

SRIM modeling results on the JDSU-coated a-Si V1 solar cells suggested the use of 600 keV protons to greatly damage the junction region. The dashed line-solid line comparison demonstrates the results in this case. The lower energy protons cause greater degradation than the penetrating protons, as predicted. This work continues at The Aerospace Corporation with bare solar cells to close in on the most damaging proton energies.

Figure 3 compares normalized Pmp as a function of increasing proton fluence for all irradiations performed at NRL on CIGS solar cells. Data points are averages of three solar cell results, and the error bars represent the standard deviation. The solid lines represent results post 3 MeV proton irradiations in the dark (penetrating) for CIGS V2 + JDSU coating and CIGS V3 bare solar cells. The dashed line represents the results for 940 keV proton irradiation on CIGS V2 + JDSU coating, modeled as highly damaging. Irradiations under illumination are on-going and no data are yet available. The large error bars on the CIGS V2 3 MeV data are due to one cell failure, which skews the average from 0.63 to 0.46. Short-circuit current dropped significantly in this cell, suggesting the contact scheme may have been compromised.

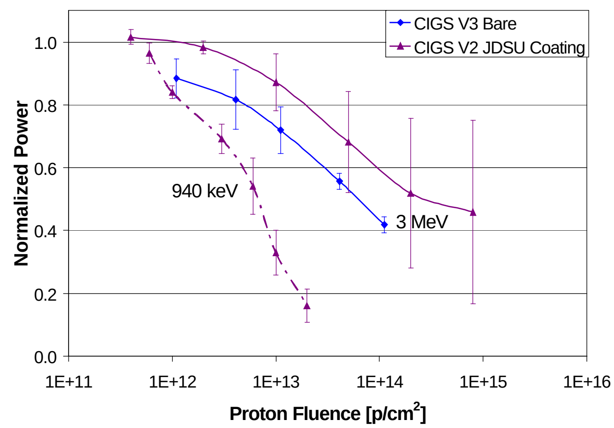

Figure 3. Normalized power as a function of proton fluence for CIGS. Solid lines: 3 MeV protons, dark. Dashed line: 940 keV protons, dark.

The effects on the coating are more difficult to determine in the CIGS case, since the solar cell manufacturers are different for the bare and coated samples. The coated samples survive the penetrating protons better than the bare samples. This points more toward the need to evaluate each manufacturer's solar cells than to a true assessment of the coating.

SRIM modeling results on the JDSU-coated CIGS V2 suggested that 940 keV protons will damage the junction region. The dashed line to solid line comparison demonstrates the results in this case. As in the a-Si case, the lower energy protons cause greater degradation than the penetrating protons, as predicted. This work continues at The Aerospace Corporation with bare solar cells to close in on the most damaging proton energies.

Dark annealing at 70ºC for 24 hours is currently being performed on selected samples at NRL.

Electron Irradiation

Figures 4 and 5 show the normalized Pmp results of 1 MeV and 0.6 MeV electron irradiation on CIGS V2 (Fig. 4) and a-Si V1 (Fig. 5) bare and coated samples, performed at JPL. Data points are averages of four or five solar cell results, and the error bars represent the standard deviation. The solid lines represent results for the 1 MeV electron irradiations in the dark and the dashed lines represent the results for 0.6 MeV electron irradiations. For the electrons, the fluences used are typical of those generally used for assessing LEO and GEO orbits. Fig. 1

demonstrates the similarity of the expected MEO and GEO electron spectra.

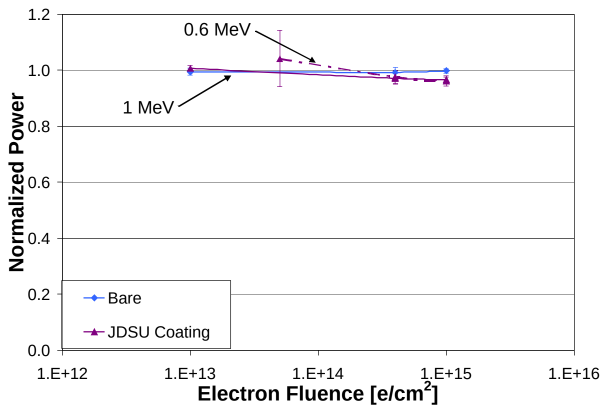

Figure 4. Normalized power as a function of electron fluence for CIGS. Solid lines: 1 MeV electrons. Dashed line: 0.6 MeV electrons.

The CIGS results in Figure 4 are well-behaved and match electron irradiation results of CIGS solar cells reported by other groups [4, 5, 11], demonstrating again the electron radiation hardness of this material. In addition, little difference is observed between the coated and bare solar cells.

The a-Si results are shown in Figure 5. Several coated cells on three of the plates shorted out during irradiation, likely due to mechanical issues. These cells were removed from the analysis, and will be inspected closely upon return of the plates to AFRL.

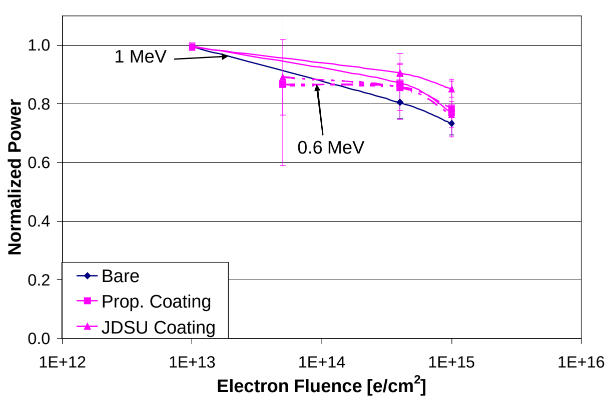

Figure 5. Normalized power as a function of electron fluence for a-Si. Solid lines: 1 MeV electrons. Dashed line: 0.6 MeV electrons.

The results of the 0.6 MeV irradiations are unusual. Typically solar cells degrade more with increasing electron energy. In this case, the degradation is nearly equivalent to or greater than the degradation due to 1 MeV electrons.

The coatings on a-Si solar cells hold up well under electron bombardment as compared with the bare cell results. In addition, increased degradation under 0.6 MeV irradiation as compared with 1 MeV irradiation is due to FF and voltage degradation, not current loss, suggesting no significant darkening of the coatings at these energies and fluences.

All electron samples are currently undergoing illuminated annealing at 70ºC for 24 hours.

SUMMARY

The response of a-Si and CIGS solar cells to penetrating and junction-damaging proton irradiation and to 0.6 MeV and 1 MeV electron irradiation has been presented. Room temperature irradiation performed with the cells in the dark and unbiased caused degradation in the Fill Factor and hence maximum power. Lower energy proton irradiation clearly demonstrates damage to the junctions, as predicted. Coated and uncoated cells behaved similarly, demonstrating the hardness of the coatings as well as the solar cell materials. 50-65^{o}C proton irradiations performed on a-Si cells under illumination and at load cause almost no degradation. These results clearly establish the enhanced proton radiation resistance of a-Si devices under operational conditions. Similar experiments are underway on CIGS samples. In addition, post-irradiation annealing is on-going. All these experiments should clarify the degradation mechanisms and support on-orbit performance models.

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